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A Case Study in Technology Utilization

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FRACTURE MECHANICS

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A CASE STUDY IN
TECHNOLOGY UTILIZATION

FRACTURE MECHANICS

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INTRODUCTION

The safety of engineering structures is often taken for granted because of the infrequent occurrence of so-called man-made catastrophes. As a result, few people have an appreciation for the diligence that designers of critical structures such as aircraft, bridges, and nuclear reactors bring to their task. Thus this study provides a focus, first on the emerging discipline of fracture mechanics and how it is helping to make engineering structures safer, and second on a unique role for the Space Agency as a direct contributor of beneficial technology for society.

The emergence and rapid acceptance of fracture mechanics during the past decade has established a new benchmark for best practice in the design and construction of critical structures. This highly technological discipline promises virtually to eliminate the hazard of catastrophic structural failure. At the heart of fracture mechanics is an understanding of the influence of cracks and crack growth on the integrity of structures. Using the concepts of fracture mechanics, the engineer often can guarantee that the structure he designs does not contain flaws which will lead to failure during its service life. For aircraft that will carry passengers for 25 years, nuclear reactors that will generate power for 40 years, and bridges that will carry traffic for 100 years, this capability is vital.

A second major focus is the study of a little-known role for NASA within specialized technical communities. Because of its specific mission requirements, many of the Space Agency's contributions to technology find other use only after some modification has taken place. In fact, previous reports in this series--plastics, lubrication, contamination control, fire safety, cryogenics, and nondestructive testing--have all focused on such transfers of NASA-generated technology. This study, by contrast, considers NASA technology which was adopted by nonaerospace engineers with little or no adaptation. Space Agency scientists and engineers often are part of a technical community whose members share a common concern for special technical problems. In such instances, innovations produced by NASA to achieve its mission objectives can be readily applied to nonaerospace problems and thus diffuse through a community to become incorporated in common practice.

SECTION I. AN OVERVIEW

On December 15, 1967, shortly before 5:00 p.m., the Point Pleasant bridge began vibrating in an abnormal fashion. The unusual vibration was accompanied by a series of loud cracks and "sonic booms." Suddenly and unexpectedly the bridge collapsed, dropping twenty-four vehicles into the Ohio River and causing the death of forty-six persons as well as injuries to nine others. The conditions surrounding the incident were perplexing. The bridge was built in 1926 and had received normal maintenance and inspection. Although designed for three lanes of traffic, the bridge was actually constructed with only two lanes and a sidewalk for pedestrians inside the stiffening trusses. Actual load at the time of collapse was 40 percent of the design load; the wind velocity was only six miles per hour (National Transportation Safety Board, 1970).

Consider another incident. On January 16, 1943, a T-2 tanker lying quietly at her fitting-out pier in Portland, Oregon issued a loud audible report that was heard for miles and cracked almost in half. The sea was calm, the weather mild, and deck stresses were very low. The incident was not an isolated case. Nineteen welded ships over 350 feet in length broke completely in two or were abandoned after severe cracking between 1941 and 1953. Less serious fractures were discovered in over 1, 500 such ships during the same time period (Parker, 1957).

Transmission pipelines have also failed dramatically. Once a crack is started in a pressurized pipeline, it races through the material at sonic speeds, unaffected by the pressure being relieved in its wake. Miles of pipeline have been destroyed during a single event, and the escaping gases create an equal or even greater hazard. Literally hundreds of other incidences involving storage tanks, bridges, aircraft, and many other structures which have all failed in such startling fashion can be cited (Parker, 1957).

Materials Containing Flaws

What causes such calamities? Is there a common factor in these failures or is each one unique? The answer to these questions and many others lies in an understanding of the behavior of materials in the presence of cracks and crack-like flaws. A large, solid-propellant rocket motor case, for example, failed during hydrostatic proof-testing at less than one-half the design yield strength. The failure originated at a small crack-like defect in a repair weld. The triggering defect involved less than 0.02 percent of the load-carrying area of the motor case wall, yet the load-carrying capacity was cut in half (Srawley and Esgar, 1966).

All engineering materials start with imperfections. Subsequent manufacturing and processing operations produce additional cracks, inclusions and other deficiencies. Such flaws can range in size from the microscopic to the very large. Surprisingly, the large flaws often do not represent as serious a threat to structural integrity because they are more easily detected. The undetected smaller cracks, however, can grow to critical size as a result of service loading and environmental conditions. Once a crack has grown to critical size, it travels freely through a part with little or no increase in load.

Because of their inability to analyze fracture behavior, many engineers specify ductile materials for fabrication of critical structures. Although these materials have a greater tolerance for flaws, they also have lower strength. Ductile materials, therefore, offer an alternative for the problems of material fracture; but this advantage must be paid for by heavier, bulkier, and less efficient structural design.

Aerospace engineers seldom have the option of using ductile materials, however. The ever-present concern for weight in aerospace designs has forced the development and application of many high-strength materials. Such materials typically fail in a brittle manner. When they do, stresses very near a flaw exceed the strength of the material, even though average stresses in the part are very low. Therefore, the safe design of many aerospace structures demands a thorough understanding of the behavior of a material in the presence of flaws.

The Evolution of Fracture Mechanics

Dealing with the problems of material fracture requires a radical departure from conventional engineering practice. After years of education and experience which relied on the assumption of a defect-free material, the engineer is forced to acknowledge the presence of flaws in a structure. Accepting this fact, his problem then becomes one of assessing the integrity of a material for its intended use. Herein lies the domain of fracture mechanics.

Much of the credit for laying the foundations of fracture mechanics, as it is practiced today, belongs to A. A. Griffith. In a pioneering paper published in 1920, Griffith proposed that an existing crack will propagate if the available elastic strain energy exceeds the increase in surface energy of the crack (Griffith, 1920). Dr. George Irwin and E. Orowan expanded the Griffith theory with two significant contributions to the understanding of material fracture: (1) a proposal that the Griffith-type energy balance must be altered to include plastic fracture work (Irwin, 1948); and (2) that fracture occurs when a critical stress distribution, characteristic of a material, is reached (Irwin, 1957). This later work served as the theoretical basis for the concept of plane strain fracture toughness and the development of an associated test method by engineers at the NASA Lewis Research Center (Brown and Srawley, 1966).

The plane strain fracture toughness test is used to determine a material property (K_{IC}) which quantitatively relates the critical crack size to applied load and geometry of a structure. The determination of K_{IC} (plane strain fracture toughness, or critical stress intensity factor) thus provides the cornerstone to structural design and analysis based on fracture mechanics concepts. At its present state of development, fracture mechanics analysis and test data are used to predict critical flaw sizes and failure modes, to estimate minimum structural loads, to establish proof-test procedures, to provide a basis for establishing nondestructive inspection acceptance criteria, to compare candidate materials, to assist in new alloy development and heat treating, and to assist in failure analysis.

Dimensions of the Field--Economic

Although the engineering applications of fracture mechanics concepts are relatively new, they have become widely accepted and employed in the design of aircraft, reactors, ships, turbines and many other structures. The economic dimensions of several industries that integrally rely upon fracture mechanics in the design, inspection, and maintenance of critical structures are reviewed below. The areas reviewed are by no means exhaustive, but are merely intended to illustrate the types of applications in which fracture mechanics has become vital.

Aircraft. Annual aircraft shipments in 1970 were estimated at 14,740, down from the all-time high of 19,367 in 1968. Value of

1970 aircraft shipments was estimated to be almost $8 billion. Total aerospace shipments including aircraft, engines and engine parts, and missiles and space vehicles exceeded $22 billion. Although the downtrend is expected to continue through 1973, the last half of the 1970's should experience a reverse in the trend. By 1980, for example, airline passenger mileage is expected to be more than triple the 1970 total of 130 billion revenue-passenger miles (U.S. Department of Commerce, 1970).

Steam engines and turbines. Electric utilities, gas and oil, and processing industries have been major users of turbine-powered equipment. In the very near future, the gas turbine industry will be an important supplier of prime mechanical drive power for land and marine vehicles, construction machinery, and similar manufacturing and construction industries. Total value of shipments for the 1960-1970 period is shown in Figure I-1.

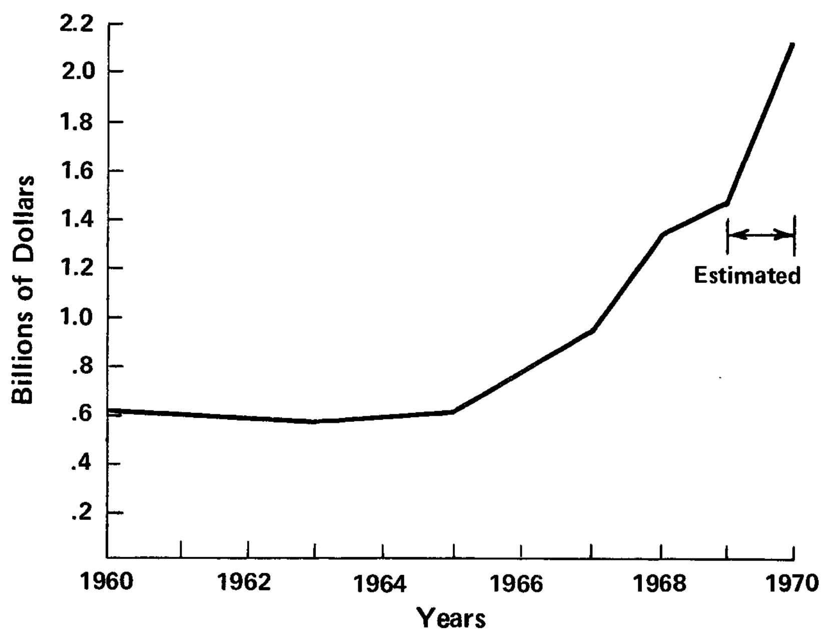

Figure I-1. Value of Turbine and Turbine Generator Shipments 1960-1970. [Source: U.S. Department of Commerce, 1970.]

The U.S. demand for electric power is expected to increase at an even faster rate in the next decade. Increased construction of "total electric" buildings, electric furnaces for steel and other process industries, and electric rail transit systems will expand steam engine and turbine markets in the seventies in order to generate the required electrical power (U.S. Department of Commerce, 1970).

Nuclear reactors. Abundant electric energy is essential to industrialization and general economic growth. The lower fuel and pollution control costs advantages of nuclear power generation will make it a crucial energy source in the future. In 1969, nuclear capacity accounted for 38 percent of the electric utility industry's total expansion program. Although the market for nuclear power generating equipment is just developing, industry and government officials estimate a world-wide market of $5 billion by 1975. The development of breeder reactors, which are expected to utilize over 50 percent of the latent fuel energy (as compared to 2 percent in present commercial reactors), will further enhance this means of power generation (U.S. Department of Commerce, 1970).

Shipbuilding. The economic and technological outlook for the shipbuilding industry is the brightest in many years. The merchant shipbuilding picture at present is particularly encouraging as a result of the confluence of several positive factors. These include: (1) a national awareness of and concern for the obsolescence of naval as well as merchant ships; (2) the need for and demonstrated advantages of new types of ships being designed and built; and (3) the discovery of oil on the Alaskan North Slope. A new program, representing a threefold increase in subsidized shipbuilding, anticipates government-supported construction of an average of 30 ships each year. U.S. privately owned shipyards completed about $3 billion worth of new ships and repair work in 1970, up 5 percent from 1969. Although there were fewer new ships delivered in 1970 as compared with 1969, dead weight tonnage increased by almost 20 percent (U.S. Department of Commerce, 1970).

Trends in the Growth of Fracture Mechanics

The emerging discipline of fracture mechanics is literally bubbling with technological activity on two fronts: the first is a continuing, strong research effort aimed at acquiring an even better understanding of the basic phenomena involved; and the second is characterized by a burgeoning of new engineering applications. The

Griffith-Irwin theory of fracture mechanics has been extremely useful in treating a special set of fracture problems related to high-strength materials and thick sections. The primary limitation of linear elastic fracture mechanics to date is that at stress levels near the yield strength of a material, fracture cannot be described by the critical stress intensity factor (Brown and Srawley, 1966). What is needed is a quantitative way of predicting fracture toughness of ductile materials. Such an explanation will come from the domain of plastic fracture mechanics.

Since fracture mechanics is such a highly technological discipline, accomplishments in the field are only recognized by special interest groups concerned with specific engineering problems. The payoff to society will come in the virtual control of catastrophic failures, so that repeated incidences like those previously discussed will become a thing of the past. By coupling inspection data supplied by nondestructive testing along with the principles of fracture mechanics, engineers will be able to predict the service life of a structure before it is built or when an existing structure should be taken out of service.

Technological Dimensions of the Fracture Mechanics Field

Because of the manifestations of brittle fracture, namely the sudden, catastrophic failure of structures at unexpectedly low loads, early engineering efforts in this developing field were directed to the problems associated with brittle fracture of materials. These principles have since grown to encompass many types of engineering structural failures; the element common to all being the influence of cracks on a material under load. The following brief sketch of some common failure mechanisms provides an indication of the technological dimensions of the field of fracture mechanics.

Brittle fracture. Although brittle fracture is most often associated with high-strength materials, several factors can cause a normally ductile material to fail in a brittle manner. One of the most important of these factors is thickness (see Figure I-2). Thick sections, as commonly used in the construction of pressure vessels, for example, fail in a brittle manner because of the resistance offered to local yielding. Clearly, increased thickness is not always the answer to increased service life.

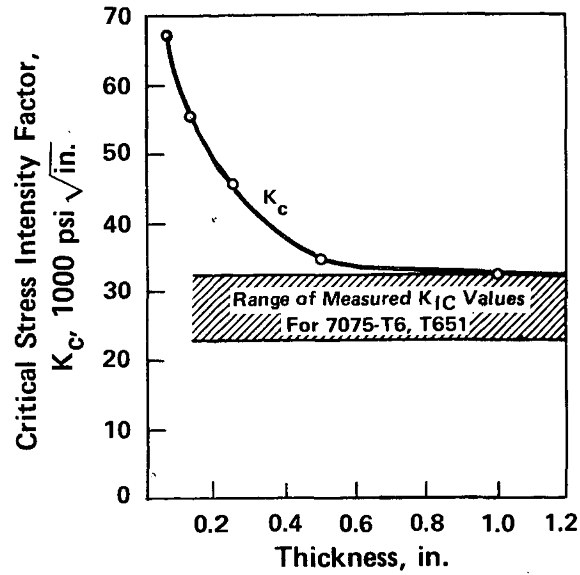

Figure I-2. Fracture Toughness of 7075-T6, T651 Sheet and Plate From Tests of Fatigue-Cracked Center-Notched Specimens (Transverse). [Source: Kaufman, 1970.]

Temperature is another important factor that can cause brittle fracture. Ferritic steels and some titanium alloys have a temperature below which they become brittle (see Figure I-3). A common and often costly mistake is made when materials which are ductile at room temperatures are employed at service temperatures below the ductile-brittle temperature transition range. One of the important findings in the laboratory investigations supporting the failure analysis of the Point Pleasant bridge was that "the A7-24 steel in this structure, when at the 32°F temperature which existed at the time of collapse, was operating below its transition temperature" (National Transportation Safety Board, 1970). At this temperature the steel had very low energy absorption capacity, approximately one-fourth that exhibited at room temperature or above.

Welding can influence the fracture strength of a material in many ways. Both lack of penetration and lack of fusion produce crack-like flaws. Additionally, rapid cooldown within the heat-affected weld zone can cause brittleness and create residual stresses. Not surprisingly, the fractures of many of the Liberty ships and T-2 tankers were directly traceable to weld defects in these ships.

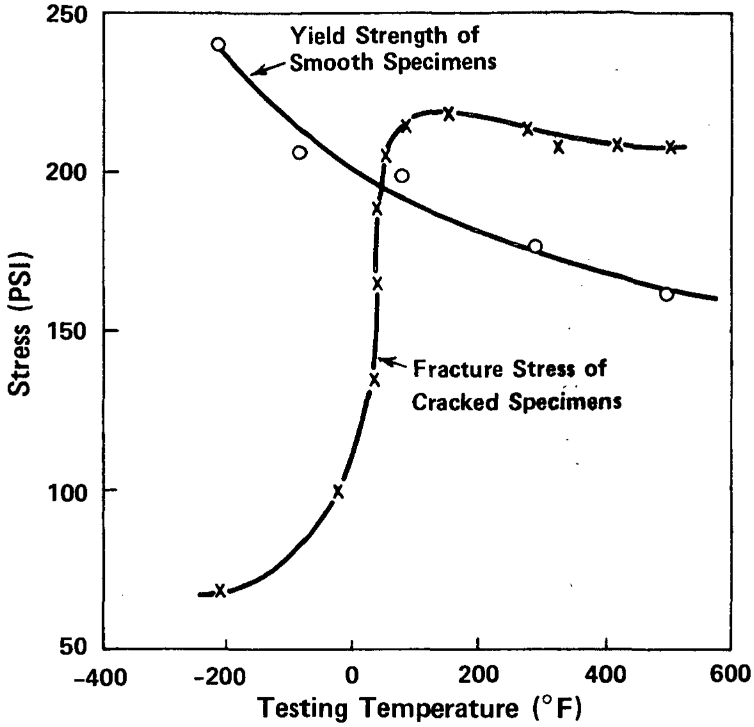

Figure I-3. Data for a Martensitic Stainless Steel Sheet Alloy (0.010 inch thick) Showing the Damaging Effect of Low Temperature on the Strength of Cracked Specimens. [Srawley and Beachem, 1959.]

Heat treatment and cold working of alloys are processes used to increase a material's strength properties, but such processing can also result in a drastic drop in fracture toughness. Figure I-4 shows the conventional tensile properties of a high-strength stainless steel as a function of tempering temperature. Also shown is the sharp-notch strength of the material. Note that in the recommended tempering range the yield strength is highest, but the sharp-notch strength is lowest (Shannon and Brown, 1970).

Fatigue. As the name implies, fatigue represents a tiring or weakening of a material with time. More specifically, fatigue deals with the influence of repeated cycling on crack growth. Since fracture mechanics considers the energy required for crack initiation and growth as well as the effects of geometric factors on crack propagation, fracture mechanics and fatigue have become interdependent disciplines. Figure I-5

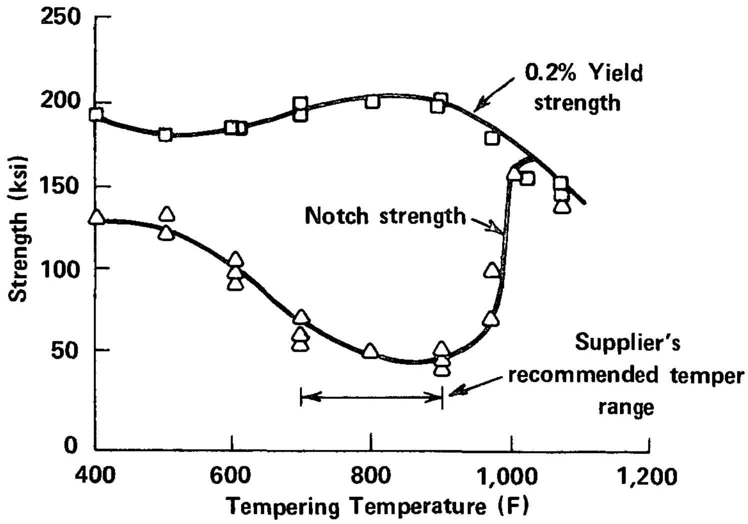

Figure I-4. Effect of Tempering Temperature on Sharp-Notch Strength of 12 MoV Stainless Steel, Using Notches with Radii Less Than 0.5 mil. [Espey, et al., 1959.]

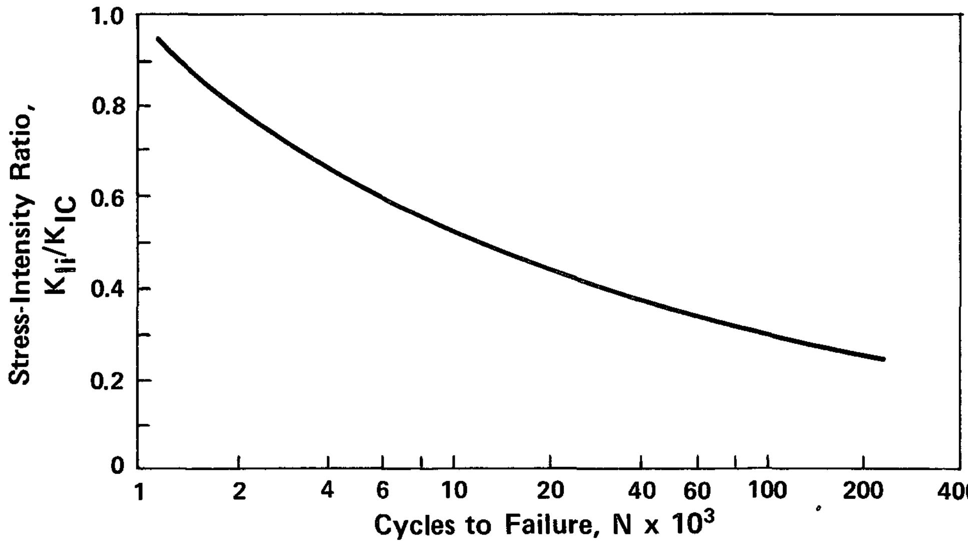

Figure I-5. Cyclic Flaw Growth for 7079-T6 Aluminum Plate. One-Inch Thick Specimens, With a K_{IC} of 34 ksi-in.$^{\frac{1}{2}}$ and a Yield Strength of 65 ksi, Were Cycled at 1,800 rpm. [Source: Forsyth, 1969.]

illustrates the fatigue and growth rate for a common aluminum alloy. Aircraft, rockets, turbines, and reactors are just a few of the structures which are deeply concerned with fatigue failure and, as a consequence, fracture mechanics.

Stress corrosion and corrosion fatigue. Many metals experience accelerated crack growth under the joint action of a steady stress and the presence of a corrosive environment. Aluminum alloys, for example, are prone to stress corrosion cracking in a marine environment; yet when not under stress they show at most only the slightest evidence of corrosive action. For years the Metallurgy Division of the Naval Research Laboratory in Washington, D.C. has conducted extensive research on stress corrosion of ship steels containing cracks.

For certain metals the presence of corrosive factors can greatly reduce the fatigue life of a structure. In circumstances of corrosion fatigue, the metal surface affected fails to develop a protective oxide or corrosive product film, and corrosion pits are allowed to form. In the failure of the Point Pleasant bridge the investigating committee concluded that "the fracture was caused by the development of a critical size flaw over the 40-year life of the structure as a result of the joint action of stress corrosion and corrosion fatigue" (National Transportation Safety Board, 1970).

Conclusion

The engineering specialty of fracture mechanics clearly has no associated industrial base, yet its application in the design of industrial equipment and structures is pervasive. This field is representative of a common class in which the discipline rather than industrial activity must be understood in order to assess the importance of the developments that are taking place. Section II examines contributions that NASA has made to the maturity of this field, contributions that lead to safer and more reliable engineering structures for the nation's growth.

SECTION II. NASA CONTRIBUTIONS TO FRACTURE MECHANICS

Conventional design engineering practice has relied on several established criteria for assessing a material's ability to resist brittle fracture. Percent elongation--one measure of the amount of deformation present in the vicinity of a fracture--is a widely accepted index of ductility. Another criterion, based on the Charpy impact test, is used to determine the temperature at which a material loses ductility and becomes brittle. In the Charpy test, a V-notched specimen, which is supported at both ends, is broken by the impact of a falling pendulum. The energy absorbed in breaking the specimen is an indication of its ductility. The inadequacy of these traditional ductility measurements when used to determine a material's sensitivity to cracks is illustrated in Figure II-1.

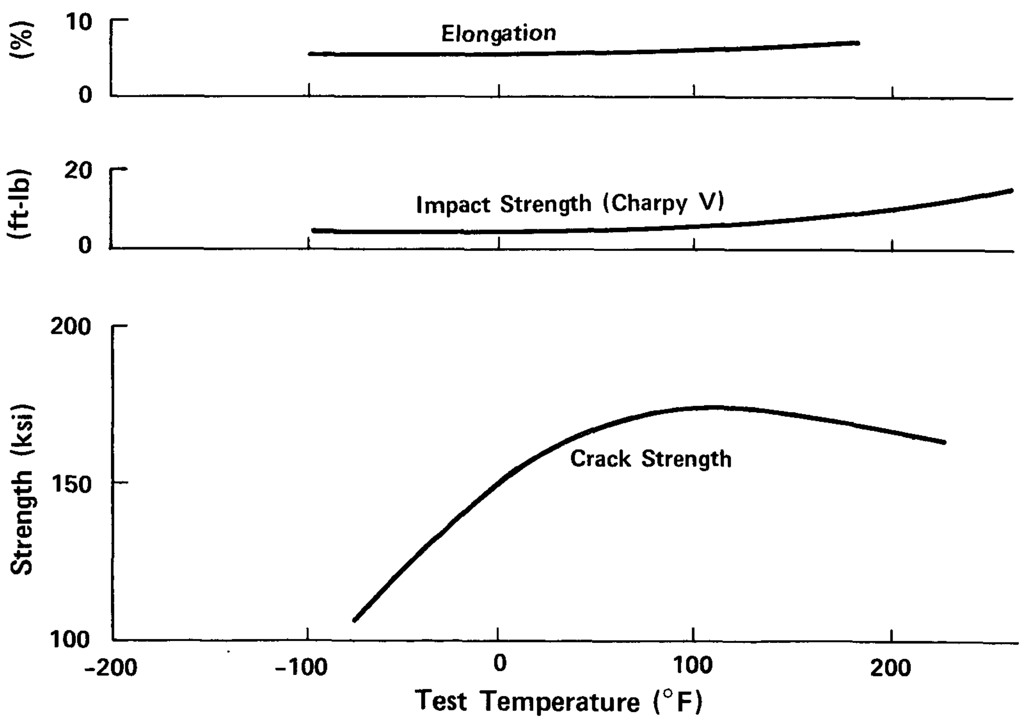

Figure II-1. Elongation, Impact and Crack Strength Properties for SAE 4335 V Low Alloy Steel as a Function of Test Temperature. [Source: Shannon and Brown, 1970.]

Neither the percent elongation nor the Charpy impact strength hint at the sharply reduced crack strength of the material when used at normal temperatures. The problem here is simply that the conventional ductility measurements deal with the gross characteristics of a materail while failure of a structure too often is the result of local characteristics, such as flaws which grow to a critical size during service life. Such flaws become the essential consideration in designs which cannot be conservative for cost, weight or size reasons. In these instances, where high performance materials are used, the fracture toughness of a material is the crucial parameter rather than ductility, and the behavior of materials can only be described through the concepts of fracture mechanics.

Engineers at NASA's Lewis and Langley Research Centers as well as at contractors' facilities have made major contributions to the development and understanding of fracture mechanics. These contributions are primarily evidenced in the development of fracture toughness test methods and the application of fracture mechanics to structural design and analysis.

Fracture Toughness Test Methods

Research conducted in the Strength of Materials Branch at NASA Lewis has been directed at two closely related objectives: (1) the development of a quantitative measure of fracture toughness to assist in structural design and proof-testing; and (2) the development of test methods for qualitative evaluation of crack propagation resistance that would be useful as a screening tool in alloy development and material selection.

Because of a close working relationship between NASA and the American Society for Testing and Materials (ASTM), the vast majority of this work has surfaced in the nonaerospace community through the activities of the ASTM E-24 Committee on Fracture Testing of Metals. This committee was formed in 1959 at the suggestion of the National Academy of Science and the Department of Defense to study the problems of brittle fracture. Their first job was to develop a test method that would permit a rational selection of steels and design loads for the Polaris motor cases and thereby put an end to a continuous series of failures which had become a national emergency (ASTM Bulletin, 1960). What started out as a special committee charged with the responsibility for resolution of a specific problem has subsequently grown to be the most productive and vital force in the fracture mechanics community. Because of the rapidly expanding interest in fracture, the E-24 Committee was recently restructured into several subcommittees to better serve the specific needs of its members.

NASA's contributions to the efforts of this committee have been major. In fact, since resolution of the rocket motor case problem, NASA engineers have provided a primary driving force for both technical achievement and administration of the committee. This is clearly evidenced by the close alignment of the E-24 Committee objectives with those of the Strength of Materials Branch at NASA Lewis and the cooperative effort on publications by ASTM and NASA (Shannon and Brown, 1970).

For years engineers attempted to make the evolving concepts of fracture mechanics more than just a subject of research interest. What they lacked was a way to quantitatively relate the theoretical concepts to practical structural analysis. Almost without exception, the analysis of a structural failure reflected the need for a quantitative method to measure the fracture toughness of the materials involved. With this being the situation, the development of the plane strain fracture toughness test by NASA needed little introduction. The engineering community was already prepared and could easily recognize the significance of this accomplishment. For the first time, a designer could directly relate flaw size and growth to the load-carrying capability and thereby specify the service life of the structure.

In developing the plane strain fracture toughness test, NASA engineers embarked on a monumental task spanning almost a decade. Analytical techniques and computer programs to permit calculation of stress intensity factors (K_{IC}) for a wide variety of material specimens and geometries were devised. Specimen configuration, dimensions, and preparation were evolved using the empirical techniques of linear elastic fracture mechanics. Of necessity, instrumentation was developed for measuring, recording and analyzing test data. Since a valid K_{IC} cannot be determined for all materials, criteria for establishing the validity of test results had to be carefully conceived and limitations established.

For many ductile materials it is not yet possible to determine a K_{IC} value because of the prohibitive thickness required for test specimens. Furthermore, testing in accordance with ASTM Method E 399-72 is expensive and requires relatively sophisticated laboratory practice. Yet in many instances there is a need to economically determine comparative measures of fracture toughness. In alloy development, for example, a large number of samples are required to optimize heat treatment alloy purity and temperature sensitivity. To facilitate these needs, screening tests were developed. These tests do not eliminate the need for K_{IC} measurements, but they do provide a rapid and economical means for determining the relative toughness of materials.

The ASTM Test Method for Sharp-Notch Tension Testing of High-Strength Sheet Materials (E 338-68), a commonly used screening test, was originally designed to select materials for solid propellant rocket motor cases. Two types of material specimens are recommended in this method. The first, which was developed by the Naval Research Laboratory, requires a center crack that is produced by fatigue testing. The second type, developed by NASA, uses a sharp edge-notched specimen and is more commonly used because of the ease of producing a flaw. In applying the principles of E 338-68, the ratio of notch tensile strength to yield strength is calculated to provide the relative measure of material toughness.

Fracture Mechanics Principles

The development of fracture toughness test methods was an outgrowth of linear elastic fracture mechanics. However, complex aerospace structures often present practical problems which cannot be exactly described by plane strain conditions. NASA therefore has ongoing research efforts in many aspects of fracture mechanics--attempts to apply the plane strain fracture toughness test to more and more materials continues; flaw growth characteristics in many materials are being determined by NASA and its contractors; and the behavior of many engineering structures experiencing conditions of plane stress is being studied. The unifying element in all these efforts is the emphasis on application of fracture mechanics to the practical problems confronting aerospace and nonaerospace engineers alike.

An example of the utility of fracture mechanics is offered in a study of proof-testing pressure vessels. In a proof-pressure test, a vessel is pressurized to a point greater than that normally expected in service. The assumption is that weaknesses will result in tank failure during test rather than in service. Such tests have been used for many years, although no really rational basis was available for assignment of test loads. In fact, in some cases proof tests can be either useless or accelerate damage to the structure.

Fracture mechanics, by contrast, can provide the necessary rationale for establishing the proof stress. Under appropriate circumstances, fracture mechanics procedures are able to combine information from flaw growth rate measurements with values of the plane strain fracture toughness in a calculation which will show that a specified safe service life can be expected if the proof test is passed. Thus, the test is designed so that any flaws which could grow to cause failure during service will cause fracture in the proof test (Tiffany and Masters, 1965). The significance of this procedure is that pressure vessels can now be confidently designed with a specified service life.

This procedure has produced a degree of confidence never before attainable in testing. Furthermore, this work can be expected to pave the way for confident prediction of the service life of a growing number of engineering structures.

Conclusion

This review of NASA contributions to the technology of fracture mechanics illustrates a fundamental role of the Space Agency in a single technical area. While primarily pursuing its goal of minimizing the weight of flight hardware, NASA engineers have generated innovations having broad impact in nonaerospace communities. Section III reviews how these specific NASA innovations are communicated to the technical community outside the Space Agency, and Section IV outlines current application areas.

SECTION III. DISSEMINATION OF FRACTURE TOUGHNESS INNOVATIONS

The requirement of NASA scientists and engineers to "provide for the widest practicable and appropriate dissemination" of the results of their work has led to the use, sometimes even the development, of specialized communications media. In the case of NASA's fracture mechanics research, at least five different media have operated to make nonaerospace technologists aware of emerging innovations: personal contacts, professional society committees, the open literature, NASA publications and trade journals.

Figure III-1 identifies the ways engineers in the Strength of Materials Branch at NASA's Lewis Research Center have used a variety of media to reach particular technical audiences. Of the five media illustrated, technical society committees have played a dominant communications role for the group at Lewis. This choice is a consequence of the fact that developments in a field which lead to new definitions of "best practice" for a community concerned with the technology also require standardization efforts before "best practice" can become "common practice."

To assure the broadest use of the results of this fracture testing research, NASA engineers have thus chosen to communicate with the nonaerospace technical community primarily through the publications and activities of the American Society for Testing and Materials (ASTM)--particularly its E-24 Committee on Fracture Testing of Metals. This section focuses special attention on two communications media of the ASTM--special technical publications and standards.

ASTM Special Technical Publications

Special Technical Publications (STP's) are issued by the ASTM in connection with its work of promoting materials properties knowledge and developing specifications and tests for materials. Much of the data presented in STP's results from the voluntary contributions of this country's technical authorities in industry, scientific organizations and government.

The publications pictured in Figure III-2 illustrate the results of cooperative efforts between NASA and the ASTM. ASTM STP 381,

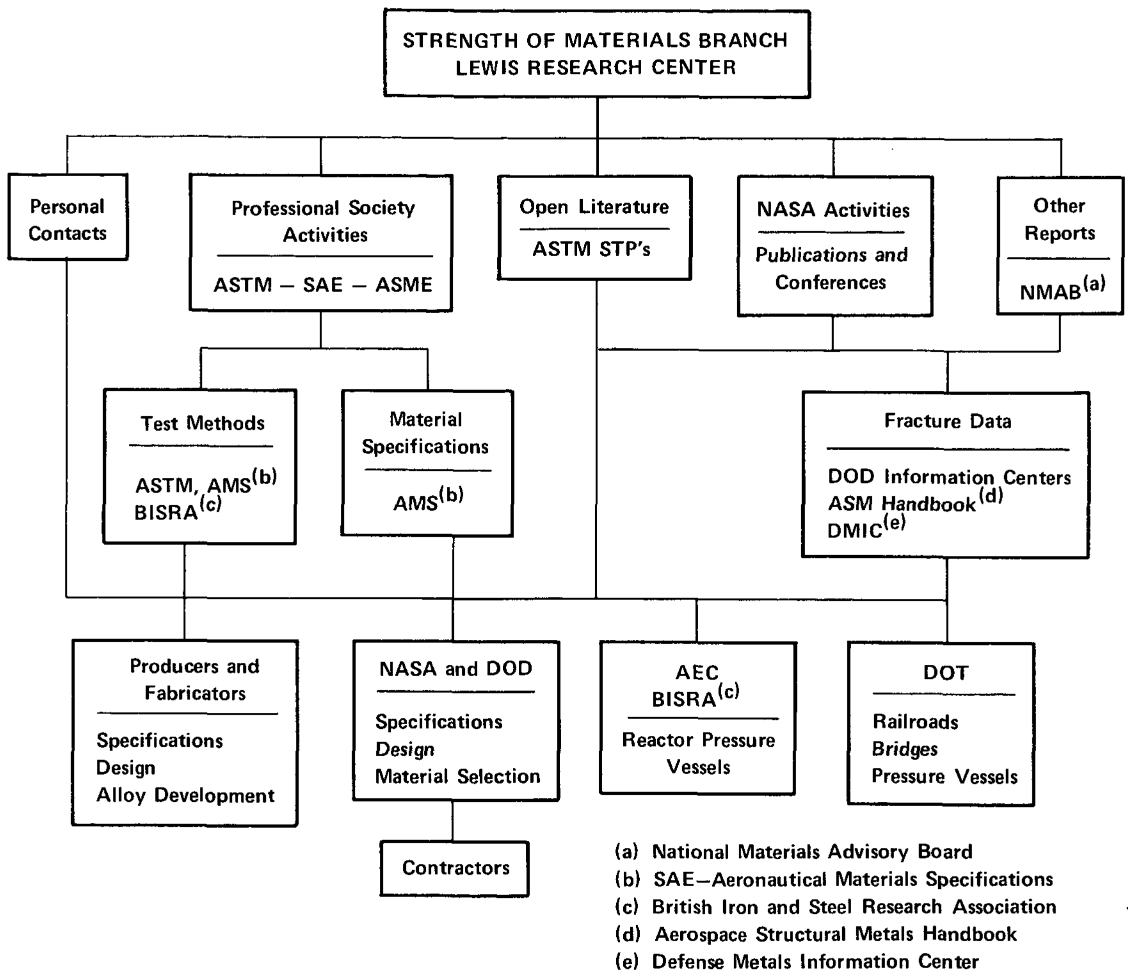

Figure III-1. Communication Activities for Engineers in the Strength of Materials Branch, Lewis Research Center. [Source: Brown, 1971.]

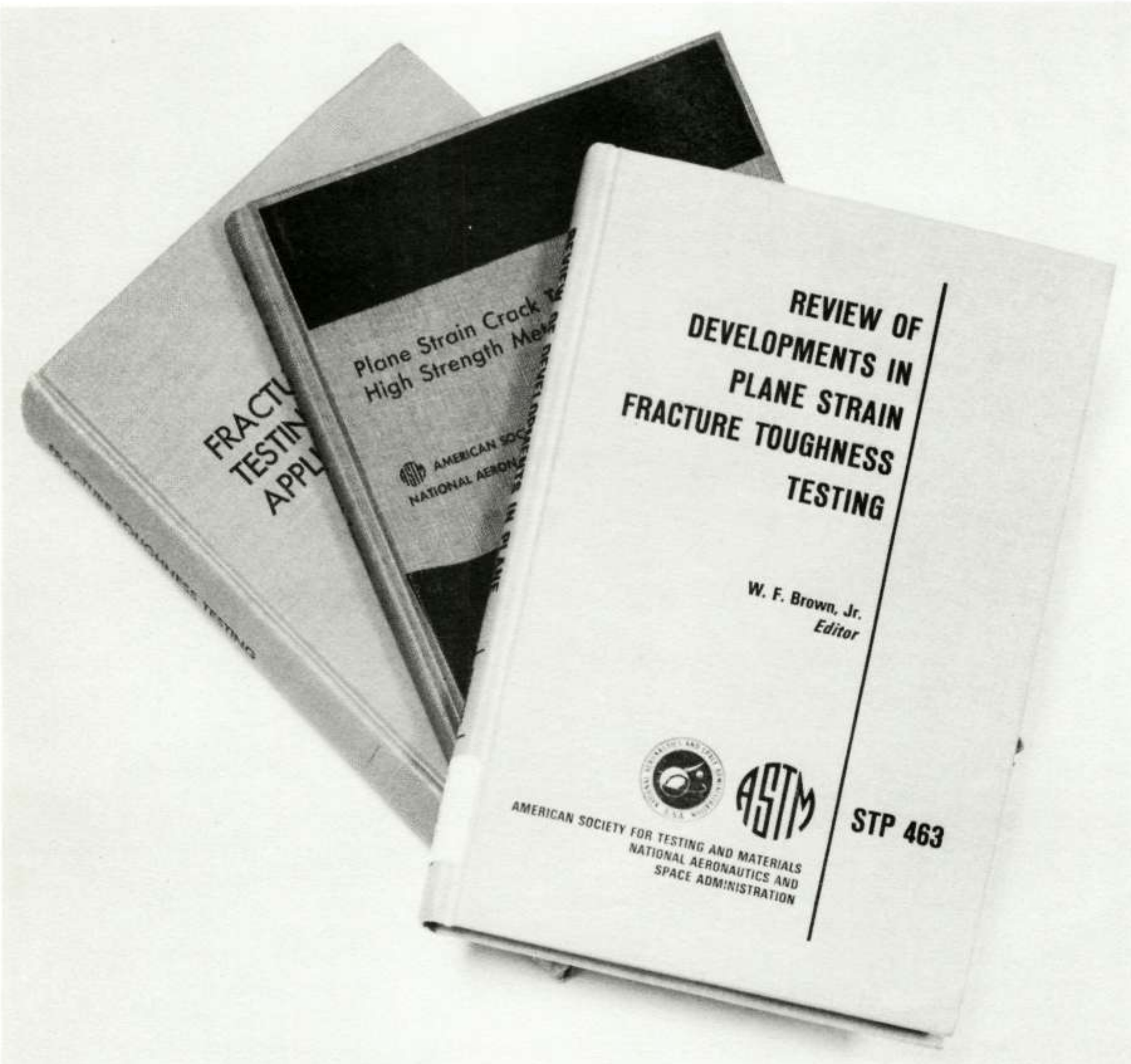

Figure III-2. ASTM/NASA Special Technical Publications on Fracture Toughness Testing.

"Fracture Toughness Testing and Its Applications," is a compilation of papers presented at a symposium held in 1964. This publication was the first of three STP's generated by the ASTM E-24 Committee. A state-of-the-art survey of the analytical and experimental basis for determining plane strain crack toughness followed in 1966. ASTM STP 410, authored by researchers at NASA Lewis, presented information which served as the basis for formulating a standard K_{IC} test. William F. Brown, Jr., of NASA Lewis authored the third publication, ASTM STP 463. This STP is a compilation of papers presented at a panel session on plane strain crack toughness sponsored by the ASTM E-24 Committee in 1970.

These documents are helping the ASTM to fulfill its obligation of providing the technical community with test methods and a sound understanding of their usefulness and limitations, while at the same time helping NASA to fulfill its commitment to wide dissemination of the results of its activities. The effectiveness of communication through these Special Technical Publications can only be inferred; ASTM reported the sale of over 7,000 copies of the three STP's by the end of 1971.

ASTM Standards

In a most fundamental way, standards are the silent language of commerce. Pipeline networks and electrical power grids, built according to national standards, distribute essential energy. Safety standards delineate the requirements for a safe home and work environment. Modern communications rely on standard symbols, drawings, magnetic ink characters and computer languages. The list is endless.

The benefits of standardization add up to: enormous savings for industry; greater safety, convenience, and lower prices for consumers; and a smoothly functioning system for national and international commerce. The following examples taken from the files of the ASTM provide an insight into the benefits of standardization and clarify why NASA pursues a broad effort to contribute to standards development.

- The inspection and testing of Portland cement [for one highway department laboratory] was erratic because of failure to follow standard testing procedures. . . . Jobs were delayed with consequent ill feelings on the part of cement manufacturers, contractors, and state highways engineers. The rigid enforcement of ASTM standard test methods . . . resulted in the elimination of disagreements, and the laboratory became one of the most reliable in the country in the opinion of cement producers and federal agencies.

- A quality control laboratory in a small knitting goods company was established, and a thorough evaluation was made of all incoming yarns in accordance with the standard ASTM test methods. This procedure reduced the mechanical breakdowns of knitters and production stoppages to the extent that the savings in a three-month period offset the cost of the test equipment and the testing labor required for a year of operation.

The entire span of today's knowledge of materials testing is reflected in the reference works of the ASTM--the world's largest non-government standards generating body. The Annual Book of ASTM Standards contains over 4,300 test methods which have been developed by the ASTM technical committees. Scientists, engineers, architects, and builders all over the world depend upon the ASTM standards for authoritative information in all aspects of evaluation and specification of materials. In 1970 alone, over 190,000 individual volumes of the ASTM standards were sold.

The method for fracture toughness testing developed by NASA has become the ASTM Standard Method E 399-72. The significance of the test method has been profound. Not only has it been incorporated in the ASTM Standards, but it has also been adopted by the Society of Automotive Engineers, the British Independent Steel Producers Association, and in MIL Handbook-5. The engineering community has literally adopted the K_{IC} designation as its primary way of speaking about fracture toughness.

Conclusion

This section has identified some of the ways engineers in the Strength of Materials Branch at NASA Lewis Research Center have chosen to communicate with their nonaerospace counterparts concerning the results of their research and development work. In examining the process by which information concerning these innovations has been disseminated, this section has also set the stage for discussing the many ways the plane strain fracture toughness test has been employed to make engineering structures safer and more reliable.

SECTION IV. DIFFUSION OF THE PLANE STRAIN FRACTURE TOUGHNESS TEST

This section reviews several instances in which individuals or firms have adopted the plane strain fracture toughness test. In each case the individuals involved have, at some time, progressed through several stages in the adoption process. This review is presented to illustrate how NASA, while in pursuit of its primary objectives, has brought about specialized major benefits to a single technical community and to society itself through that community.

The Diffusion Process

Diffusion is the result of individual decisions to accept or reject an innovation. The process has been described as a series of five stages of individual behavior: awareness, interest, evaluation, trial and adoption (Rogers, 1962). Rejection of the innovation can occur, of course, at any stage in this process. A brief case study is presented in order to clarify how engineering specialists are contributing to the diffusion of fracture mechanics technology.

Approximately two years ago, Dale Galliart, a materials engineer at Deere and Company in Moline, Illinois, became interested in fracture mechanics. His interest grew out of a continuous need to improve farm machinery manufactured by his firm. Plow blades, for example, were found to have a shorter service life even though they were made thicker.

Initially, Galliart reviewed the literature on fracture to become familiar with the concepts involved. During this experience he became aware of the plane strain fracture toughness test. Although he lacked complete information about the test, he was not motivated to seek further information about it immediately. Later, his "education" resumed as he attended a short course and a symposium on fracture mechanics. Each of these exposures to the plane strain fracture toughness test and its applications heightened his understanding of the technology. He entered the interest stage upon learning that K_{IC} values were not readily available for the materials he was accustomed to using. Galliart then obtained the ASTM STP's and standard test methods to learn more about the plane strain fracture toughness test and reinforce his interest. Throughout this learning process, he evaluated the technology against his present and anticipated work requirements. In this evaluation stage he weighed the advantages and disadvantages of the innovation in deciding whether or not to commit resources to it.

Galliart presently has proceeded through the adoption process to the trial stage, where he will attempt to make some K_{IC} measurements on a small scale using ASTM E 399-72. As a result of the trial, he hopes to learn how well the plane strain fracture toughness test meets his firm's needs. If favorable results are obtained, he will proceed to full use and become an "early" adopter of the innovation. Other examples of individuals and firms that have fully adopted the plane strain fracture toughness test follow.

Design Applications

The rapid advancement in plane strain fracture mechanics technology has been largely caused by the demands of the aerospace industry. The ever-present concern for structural weight of flight hardware has led to the development of many high-strength alloys. Characteristic of these aerospace materials is their tendency to fail in a brittle (plane strain) manner.

While most experience has been confined to relatively brittle materials, applications for the use of plane strain fracture toughness, K_{IC}, have been growing rapidly, especially in design of thick section structures. The restraint offered to plastic flow around a crack in a thick section produces a plane strain condition. In the electric power industry, for example, many structures require the use of heavy sections made from low-to-intermediate strength steels. Pressure vessels, turbine and generator rotors, and nuclear reactor shells are examples of such structures.

Westinghouse has conducted extensive research related to the application of linear elastic fracture mechanics to pressure vessels. Part of this research was directed to the creation of fracture toughness and fatigue crack growth rate data for some typical pressure vessel materials: namely ASTM A 533 and ASTM A 216 type steels. Fracture toughness data were determined: (1) over a wide range of temperatures; (2) for several specimens; and (3) for weld metal. All K_{IC} data reported were obtained with the compact tension type of specimen according to the ASTM Tentative Method of Test (ASTM E 399-70T).

With such data, the safety of large pressure vessels in any application can now be quantitatively demonstrated (Wessel, 1969).

Westinghouse has also been very active in applying linear elastic fracture mechanics technology to the design, inspection, and maintenance of large turbine generator rotors. Thus, major efforts have been devoted to the determination of fracture toughness for common rotor alloys over a wide range of temperatures and strain rates. Fatigue crack growth rates as a function of stress intensities were also determined. The three basic alloys which were evaluated (A 469, A 470 and A 471) are used for all large turbine generator rotor and disk forgings manufactured in the United States. All K_{IC} data were determined using the ASTM Tentative Method of Test E 399-70T. These data were used to establish realistic normal and maximum operating conditions, material requirements, and meaningful acceptance criteria for nondestructive testing (Greenberg, et al., 1969).

Pressure vessels and turbine rotors are just two examples of power generating equipment that embody fracture mechanics technology. Reliable, long-term operation of such equipment is vital to meeting the enormous demands for energy in this country. In 1970 alone, installed generating capacity in the United States was increased by 25 million kilowatts. This added capacity is equivalent to the electrical power requirement for 25 million homes.

The design of the new Air Force/North American Rockwell B-1 strategic bomber is relying heavily on the concepts of fracture mechanics. The B-1 is expected to serve as the primary manned strategic bomber for the remainder of this century. North American Rockwell (NAR) states that design service life is now considerably longer than for any previous bomber. The Air Force has specified the use of fracture mechanics in the design of the B-1 as an outgrowth of problems with the F-111 series of aircraft. North American Rockwell has operationalized the Air Force requirement in many ways. Each piece of titanium plate, produced in 15-to-20 foot sections, is required to have fracture toughness values determined in both longitudinal and transverse directions, at a cost of $300 for each test. In house, NAR will determine fracture toughness values for any material that undergoes processing after being delivered by a producer. NAR has now settled on a 0.13 percent maximum oxygen content for structural titanium alloys based on measured fracture toughness values (Aviation Week & Space Technology, 1971).

The Air Force anticipates a procurement of 240 aircraft at a total program cost of $11 billion. Of that cost, more than $2 billion will be channeled into research and development efforts to implement the latest advances in aircraft technology, including fracture mechanics.

Alloy Development and Property Determination

As previously discussed, the early phases of new alloy development rely heavily on screening tests for an indication of fracture toughness of a material. When the development progresses to the point of requiring quantitative data on fracture toughness, however, ASTM E 399-72 is employed to provide the required information. Furthermore, producers such as Aluminum Company of America are finding a growing number of customers demanding guaranteed minimum acceptable K_{IC} values for the materials they purchase (Kaufman, 1971).

In a typical response to such demands, U.S. Steel conducted a program to determine the plane strain fracture toughness of eleven different steels. Except for some accommodations in specimen size, the tests were conducted in accordance with the NASA-developed test procedure. The measured K_{IC} values were concluded to be reliable for general engineering application (Rolfe and Novak, 1970). Yet the most significant element here is that the burden for determination of fracture toughness values is now shifting from users, such as Westinghouse, to the primary producer of engineering materials. This shift is the result of more and more frequent specification of K_{IC} values in customer orders and is the clearest evidence of the diffusion of the technology.

British Standard for Plane Strain Fracture Toughness (K_{IC}) Testing

In the early 1960's considerable attention was focused, in the United Kingdom, on the testing of ultrahigh-strength steels and the variability between results from different laboratories. At the request of the Inter-Services Metallurgical Research Council, the British Iron and Steel Corporation (BISRA) was asked to set up a working group under its Engineering Properties Committee to consider the problems of standardization of test methods for high-strength steels. The initial aim was to improve the uniformity of testing, in particular the measurement of transverse properties and notch sensitivity, and to provide data to assist designers in selecting high-strength steels for critical applications.

In 1964 a study group was formed to consider possible test programs as well as the developments in fracture toughness testing in the United States. In view of the similar objectives, it was decided that it would be advantageous for BISRA to be represented on the ASTM Committee E-24. This made it possible for BISRA to be fully aware of the developments in the fracture toughness field and to benefit from the United States' effort. By close collaboration with the ASTM Committee E-24 on Fracture Toughness, BISRA not only benefitted from the experience in the United States, but also has become a contributor to the wealth of information in recent years. As a result of this relationship, the British Standard for fracture toughness testing (MG/EB/240/70) is essentially the NASA-developed ASTM Method (May, 1970).

Structural Evaluation

The introduction of fracture mechanics has opened a broad new horizon of evaluation capabilities to the engineer. In analysis of a failed part, for example, fracture toughness data can be used to determine if a specific flaw caused the failure.

The importance of fracture mechanics concepts in preventing disasters is even more significant. The 1968 Bridge Inspection Act requires that the 236,000 federal-aid bridges in this country be inspected at two-year intervals beginning July 1, 1973. The emerging capability of fracture mechanics will be of fundamental importance in assessing the hazard potential of the flaws that are discovered. Furthermore, these concepts will likewise facilitate interpretation of inspection data on aircraft, ships, turbines, and many other critical structures.

Engineering Education

Education for engineering students as well as practicing engineers is being revised to include the study of fracture mechanics. Courses in fracture mechanics and structural design at Lehigh University, the University of Illinois, the University of Kansas and many other schools now include specific attention to the plane strain fracture toughness test and its applications. Professional training is also underway. For example, Del Research Corporation and Instron Corporation co-sponsor a "Short Course in Fracture Mechanics" at the Instron Corporation facility near Boston. The course provides intense instruction in fracture mechanics for professionals, with activities divided between lecture and laboratory sessions devoted to fracture testing techniques.

Conclusion

The diffusion of plane strain fracture mechanics technology is clearly just beginning, and the development of the fracture toughness test was the catalyst necessary to initiate the process. At this time, it can be seen that the technology is moving into important areas of commerce and production and that the movement will be sustained by the training of new engineers in the discipline of fracture mechanics.

The importance of this technology can be deduced from the behavior of the technical community affected, since that technology is incorporated in equipment and structures that are already extremely complex. The evidence presented in this section suggests that the technical community in particular and society in general have indeed benefitted.

SECTION V. A FOCUS ON ISSUES

This Case Study in Technology Utilization illustrates how the research undertaken by NASA can have a pervasive effect on obscure but essential aspects of the American way of life. The work described and the applications found are indeed specific. Yet the significance of the study lies in the documentation of an obviously unplanned, but vital, coupling between mission-oriented research and other technological requirements on an industrial society. The fact that the coupling is unplanned comments directly on the visibility of such occurrences. There is poor visibility because there is no systematic mechanism for recording such apparently random occurrences. When one considers the breadth of NASA research and development programs, the quality of the personnel, and the effectiveness of the effort, it is easy to see that other technical communities have been affected in ways similar to those described here.

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